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Published in:
2021 IEEE Transportation Electrification Conference & Expo (ITEC)

DOI (link to publication from Publisher):
10.1109/ITEC51675.2021.9490131

Publication date:
2021

Document Version
Accepted author manuscript, peer reviewed version

Modeling In-and-Out-of-Water Impact on All-Electric Ship Power System Considering Propeller Submergence in Waves

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***Abstract-* Despite the advantages of employing an electric propulsion system in All-Electric Ships (AES), additional power fluctuation sources have emerged in the ship power system as a result. Since the propellers are the primary power consumers in the AES, these fluctuations may significantly affect its power system power quality. Thus, for optimal performance of the ship power system, these fluctuations need to be rigorously investigated at the design level of vessels. Waves collision is one of the critical conditions where propellers inject power fluctuations into the ship power system. Therefore, a comprehensive model is essential to analyze the propellers in-and-out-of-water effect on the ship power system thoroughly at the design level. This paper proposes a model-based approach for determining propeller immersion depth variations in collisions with different wave classes. According to this approach, the propellers thrust loss factor caused by the in-and-out-of-water effect can be identified. The proposed method is then applied in an integrated AES model. This model interconnects the ship motion and power system dynamics. The in-and-out-of-water impact on the ship power system can be explored precisely in the model-based design of the vessels by utilizing the proposed model. In the end, the proposed method and the interconnected model have been used to simulate a notional ship in a wave collision condition. Simulations demonstrate that the proposed approach can accurately map the substantial impacts of the vessel-wave encountering conditions on the frequency, voltage, and generally on the power quality of the AES power system.**

I. INTRODUCTION

In the last decade, connecting the electric propulsion system to the ship power system has led to superior controllability in the vessels and enhanced the efficiency of the propellers power consumption [1]. Although the integrated electric power system has presented significant benefits to the AES, it has affected the power quality and reliability of the ship power system [2]. Some of these impacts originate from the propulsion system, which has a distinct dynamic feature compared to the typical loads of terrestrial microgrids. In other words, these impacts are distinctive in the AES power system and are not a challenge for typical terrestrial microgrids [3]. Since the primary load in the AES power system is the propulsion system, exploring these impacts on the power system performance calls for novel and innovative approaches for optimal and reliable design, control, and operation of AES. These approaches must cover various fields such as stability, power quality, and operating costs of the vessels. An essential inherent attribute of the propulsion systems in ships is their torque fluctuations in wave excitation conditions [4]. The sea movements in wave collision conditions can affect the ship motion and cause substantial movements of the ship propellers relative to the sea level [5]. The propellers position shifts with respect to to the water surface can lead to the propellers thrust loss in severe to extreme conditions. The power fluctuations driven by the in-and-out-of-water impact in waves can affect the power quality through the propellers electric motors interconnection with the AES power system [6], [7]. This effect can cause a sudden thrust loss of up to 80% in extreme conditions. These fluctuations may deteriorate the efficient performance of the AES power system [8]. Furthermore, the significant thrust loss merged with the wave-frequency periodic fluctuations in the propellers power consumption can lead to severe aging as well as wear and tear of the propulsion system's mechanical parts [8]. High-frequency variations have been listed as the leading result of mechanical fatigue in the propulsion system [9].

The propulsion system fluctuations and their influences on the AES power system are explored in various studies. In [10], an open-water efficiency based strategy that can decrease the power system fluctuations in ship maneuvers is proposed. A specific ducted propeller with varying submergence has been subjected to the in-and-out-of-water effect at low advance velocities, and the experimental results are presented in [11]. These fluctuation models have been extracted from the experimental results on the propeller. As the in-and-out-of-water effect and ventilation generate considerable thrust loss in high seas, the torque and power control system of the propeller can result in propeller racing. In [12], a thruster control with an anti-spin feature is introduced by investigating the in-and-out-of-water effect experimental result. The in-and-out-of-water effect and ventilation are the primary loss effects that have been considered in [12]. In [13], random waves are modeled through the one-parameter Pierson and Moskowitz seas spectrum. Then, the stochastic responses of the model are examined in the surge motion. The low-level controllers sensitivities to undesired oscillations in normal operating conditions have been investigated in [14]. A hybrid power/torque thruster control scheme is presented in [15].

The presented controller utilizes the thrust loss estimation method in moderate and extreme seas. In [16], a controller that redistributes the power from the electric consumers to thrusters is presented. It reduces the load fluctuation sensed by the ship power system.

The above-mentioned literature has explored the in-and-out-of-water effect on the propeller in moderate to extreme conditions in their studies. Besides, some literature have investigated new approaches to reduce the power fluctuations effect of the propulsion system on the ship power system. However, these studies have commonly employed ship motion features and the wave collision effects that have been extracted from specific empirical results or a particular operation history. Therefore, these characteristics cannot model the in-and-out-of-water impacts on the ship power system during various vessel-wave encountering conditions. As a result, utilizing these characteristics at the design and control levels may not guarantee an optimal and efficient operation of the AES. Thus, an integrated and comprehensive model for analyzing the in-and-out-of-water effect of the propeller on the AES power system is crucial.

In order to address these issues, a comprehensive model considering the in-and-out-of-water effect of the propeller in the power system during a wave-encountering condition is proposed in this paper. This model will interconnect the AES power system and the ship motion during wave collisions conditions. In addition, a straightforward method for investigating the propellers submergence fluctuations during wave collision according to the ship motion angles is also proposed. By utilizing the proposed approach, the integrated model is able to explore the in-and-out-water effects on the ship power system in different conditions, such as extreme conditions and wave collisions. The proposed interconnected model yields precise analysis of the wave effects on the AES power system fluctuations. Thus, it results in a more accurate model for AES functionalities in different operational scenarios during wave-encountering conditions. More practically, this model can be used in the model-based design of AES in the marine industry. Thereby, the power system controllers can be designed and tuned considering different operating situations.

In the following, a scheme of the proposed model and its different aspects is investigated in section II. Detailed description of the proposed method for modeling the in-and-out-of-water effect during wave collision conditions is presented in section III. The proposed model has been used to simulate the power system fluctuations during a wave-encountering scenario in section IV. In the end, the effectiveness of the proposed model and future works is concluded in section V.

II. The Interconnected AES Model For Wave Collision Conditions

In order to model the in-and-out-of-water effect on the AES power system, the interconnections among mechanical, hydrodynamic, and electrical aspects of the AES have been covered in the proposed model. The framework of this integrated model is depicted in Fig. 1. The illustrated framework has two primary components: the hydrodynamic model and the power system model. The ship microgrid and its associated control system are represented in the power system model. The hydrodynamic model describes the ship motion during different operating conditions. The covered concepts in this model have been separated into three subsets: the ship motion model, the in-and-out-of-water effect model, and the propeller model. The ship motion model explores the ship angles and voyage speed according to the propellers produced thrust and rudder angles. As the propulsion system is the critical point of interconnections between the ship motion and the ship power system, it is modeled accurately in the propeller model. The change of propellers immersion depth during the collision of waves and the resulting in-and-out-of-water effect is considered in the in-and-out-of-water effect model. The mentioned models and related concepts are presented in this section. According to the focus of this paper, the proposed in-and-out-of-water effect model and the method for obtaining the propellers immersion depth are presented in section III, individually.

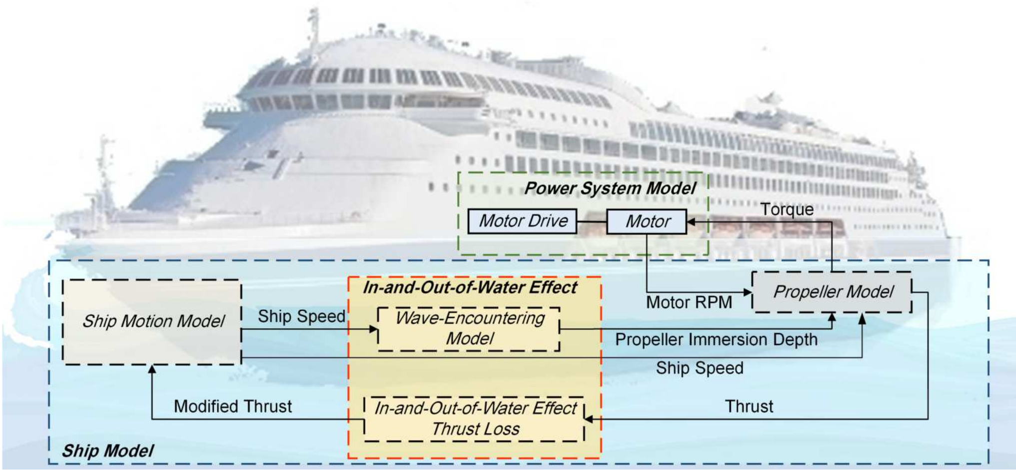

Fig. 1. The proposed interconnected model framework for investigating the in-and-out-of-water effect on the ship power system

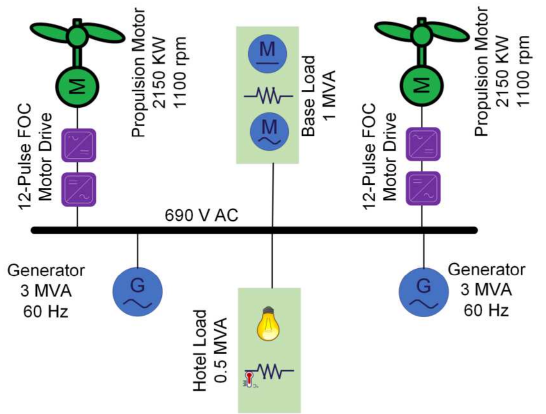

Fig. 2. A notional single line diagram of the AES power system

A. The power system model

A schematic of a notional ship power system, considering the typical power system of modern ships [17], [18], is shown in Fig. 2. The main bus voltage and frequency of the power system considered in this study are 690V and 60 Hz, respectively. It contains two salient pole diesel generators with a total generating capacity of 6 MVA. A typical governor dynamic model with a speed and temperature control loop is considered for these generators [19]. In addition, an AC1A excitation system is used to model the field voltage control of the generators [20]. The basis of this typical excitation system is an alternator exciter with non-controlled rectifiers. Two 2150 kW/1100 rpm asynchronous motors with 12-pulse field-oriented control (FOC) motor drives have been considered for the AES propulsion system. The stator current gets adjusted related to the rotor flux in the modeled motor drive. Consequently, it can control the flux and torque of the propellers motor independently [21]. Other considered loads for the AES system are a 0.5 MVA Hotel Load and a 1 MVA Base Load. The Hotel Load is the aggregated power consumption of loads such as lighting, heating, and ventilation. The power consumption of loads such as pump motors and bow thruster are included in the Base Load.

B. The ship motion model

The primary focus of the ship motion model is on analyzing the ship speed, position and route direction according to the ship motions and propellers thrust. The body-fixed coordinate system (also called hull-fixed coordinate system), which is used for the relative ship motion modeling, and the expressions are shown in Fig. 3. The assumed wave collision direction for this study, which is a heading wave, is shown in this figure. In the ship coordinates, the ship position vector (η) and the velocity vector (U) of the vessel can be expressed as follows.

$$\eta = [x \quad y \quad \psi]^T \tag{1}$$

$$U = [u \quad v \quad r]^T \tag{2}$$

where x, y are the ship position, and ψ is the yaw angle. In addition, u, v, and r are the ship's surge, sway, and yaw velocity during the maneuver.

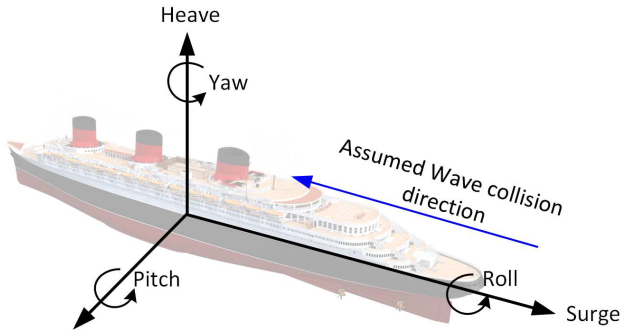

Fig. 3. The body-fixed coordinate system for the six degrees of the ship motion

Considering (1) and (2), the relationship between the ship velocity and the ship position can be expressed as below [22].

$$\dot{\eta} = R(\psi)v \tag{3}$$

According to ship angles, $R(\psi)$ can be formulated as (4).

$$R(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

In terms of the ship speed vector and the produced thrust, the ship kinematic performance can be obtained from (5) [23].

$$M\dot{U} + C(U)U + D(U)U = T \tag{5}$$

In this equation, $C(U)$ is the Coriolis centripetal force matrix, M is the ship inertia, $D(U)$ is the damping matrix, and T is the propellers produced thrust. According to the mentioned equations, the ship motion model explores the ship's route direction and speed.

C. The propeller model

The propellers torque and thrust can be expressed according to (6) and (7) [24].

$$Q = \beta_Q \rho D^5 K_Q \,|n|\, n \tag{6}$$

$$T = \beta_T \rho D^4 K_T \,|n|\, n \tag{7}$$

In (6) and (7), ρ is water density, n is the propellers speed, D is the propeller diameter, Q is the propeller toque, and T is the produced thrust. β_T and β_Q represent the thrust and torque loss factors caused by the in-and-out-of-water effect during wave collisions. These coefficients are obtained from the in-and-out-of-water effect model. Besides, K_T and K_Q are non-dimensional coefficients and are referred to as open-water characteristics of the propeller. They can be obtained from cavitation tunned or a towing tank test [24]. In this paper, a Wageningen B-series propeller open-water characteristics have been extracted and used for the model, according to [25].

III. Modeling In-And-Out-of-Water Impact on AES Power System

The in-and-out-of-water model includes two parts: the wave encounter model and the in-and-out-of-water effect thrust loss. Once a wave collides, the wave-encountering model evaluates the fluctuations in the ship coordinates according to the motion equations and the encountering wave characteristics. A closed-form expression is used for analyzing the ship motion angles according to the hull-fixed coordinates during vessel-wave encountering [26], [27]. According to the output of the wave-encountering model and the ship characteristics, such as its length, breadth, and draught, the propeller immersion depth can be obtained. A straightforward method for analyzing the propeller immersion depth fluctuations in extreme conditions is proposed and employed in the model. Fig. 4 shows the proposed approach that has been used in the model for analyzing the propeller immersion depth concerning the pitch angle during encountering waves. In this figure, the assumed angle for wave direction according to Fig. 3 is zero degrees. Thus, the modified propeller immersion depth at every instant can be expressed as:

$$H(t) = h - \frac{L}{2}(\tan(\varphi(t))) \quad (8)$$

where $H(t)$ is the propeller immersion depth at every moment, h is the initial propeller submergence in the calm waters, L is the ship length, and $\varphi(t)$ is the pitch angle obtained according to the ship motions during the wave-encountering condition. The same method can be applied for exploring the propeller immersion depth according to the roll angle changes in different wave classes collision. Following these results, the overall shift in the propeller submergence can be identified.

The shift in immersion depth will cause a thrust loss factor in the propeller. The in-and-out-of-water effect model aims to identify this thrust loss and to modify the propellers produced thrust accordingly. Various forms of expressions can be used for obtaining the thrust loss factor according to the propeller submergence. In this model, the following term, which is commonly used by ship control systems, is deployed [11], [28], :

$$\beta = \begin{cases} 0, & h/R \le -0.48 \\ 1 - 0.675(1 - 0.769h/R)^{1.258}, & -0.48 < h/R < 1.3 \\ 1, & h/R \ge 1.3 \end{cases} \quad (9)$$

where β denotes the in-and-out-of-water thrust loss factor, h is the propeller immersion depth, and R is the radius of the propeller. The wave collision causes a change in the propeller torque. Thus, the electric power consumption of the propulsion system will fluctuate. It ends up in frequency and voltage variations in the AES power system. These fluctuations can be investigated using the proposed model and its interconnections. In the next section, a case study of ship operating conditions in waves is presented. Then, by investigating the proposed method and exploring the propeller submergence changes, the in-and-out-of-water effect on the frequency and voltage fluctuation of the AES power system is illustrated.

IV. SIMULATION

In this section, an operation condition in which the ship will encounter waves from the bow side (the front side of the vessel) is investigated. The ship and wave characteristics that are used for this case study are summarized in Table 1. In addition, Fig. 5 shows a graphical view of the wave that encounters the vessel in the assumed sea environment. The simulation results show the effectiveness of the proposed method for obtaining the propeller immersion depth in the interconnected model. Fig. 6 illustrates the ship roll and pitch angle changes during this situation. As expected, when the heading wave encounters, the roll angle does not change (as shown in red in Fig. 6). However, the pitch angle of the ship is changed up to 9.2 degrees when the wave reaches its peak amplitude.

According to the proposed approach and the identified ship motion angles, the propeller submergence fluctuation is depicted in Fig. 7. These shifts in the propellers immersion depth relative to the sea level will result in the propellers thrust loss factor in the wave collision condition. The related thrust loss factor (β in (9)) is demonstrated in Fig. 8. It is observed that the amplitude of the thrust loss can be as high as 60 percent of the produced thrust. Fig. 9 depicts the propellers power consumption fluctuations caused by the in-and-out-of-water effect. It is shown that the propellers power consumption be change up to 28.4 percent during the assumed wave collision. Since the propulsion system is the primary power consumer in the AES power system, this power fluctuation may decrease the power quality of the ship power system. The voltage and frequency fluctuations of the AES power system during the assumed wave encountering condition are shown in Fig. 10 and Fig. 11, respectively. As shown in these figures, at the peak height of the wave, the

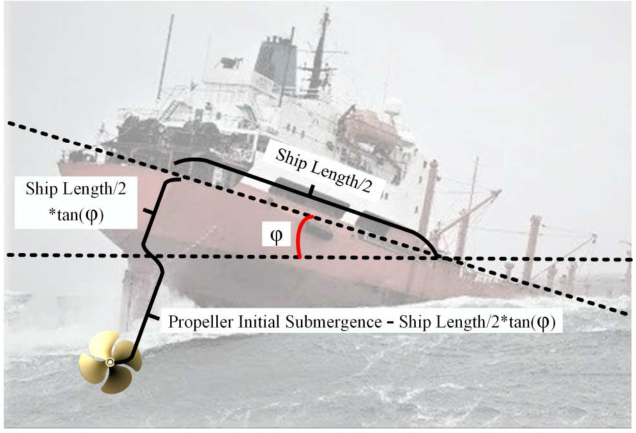

Fig. 4 The proposed method for modelling the propeller submergence fluctuations during wave encountering

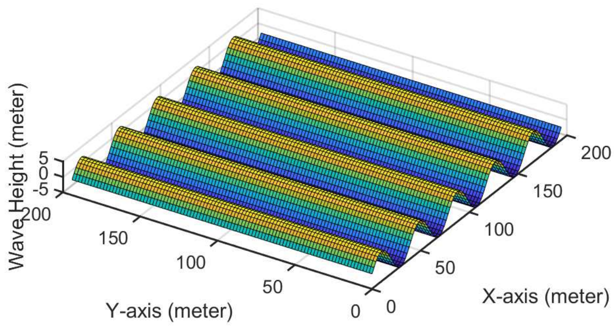

Fig. 5. The regular wave encountering with the vessel in the sea environment

power system frequency will increase 1.02 percent, and the voltage will rise 1.1 percent. The demonstrated results show that the proposed model can model the wave impact on the AES power system in any wave classes and collision direction angles. In contrast, conventional approaches employ predefined empirical wave and electric power characteristics for several operating conditions. Therefore, the conventional methods cannot (theoretically) model the power system fluctuations in operation conditions beyond their prespecified situations. The proposed approach can appropriately model the interactions between ship motion and the AES power system. As a result, the impact of any ship motion in waves can be projected adequately to the electrical side of the AES. This will facilitate a model-based design and operation of AES, considering various operation mission profiles.

When a wave encounters the ship from different angles rather than the front of the vessel, it will result in more significant fluctuations, especially in the vessels with two propellers. Since changing the roll angle in these ships will result in different in-and-out-of-water effects in each propeller according to wave periods, it will have a substantial impact on the AES power system, which can be modeled by the proposed model.

V. CONCLUSION

This paper has proposed a simple method for investigating the in-and-out-of-water effect on the all-electric ship power system. The proposed approach considers ship motion angles during wave collision conditions and explores the propeller submergence changes accordingly. Then, concerning the proposed method, a comprehensive and interconnected ship model for analyzing the impacts of the propeller immersion

TABLE 1. THE SHIP AND THE ENCOUNTERING WAVE PARAMETERS

Parameter	Value	Parameter	Value
Ship length	82.8 m	Propeller diameter	5 m
Ship breadth	19.2 m	Number of blades	4
Propeller submergence	7 m	Ship speed	18 knots
Wave amplitude	5 m	Wave period	10 s

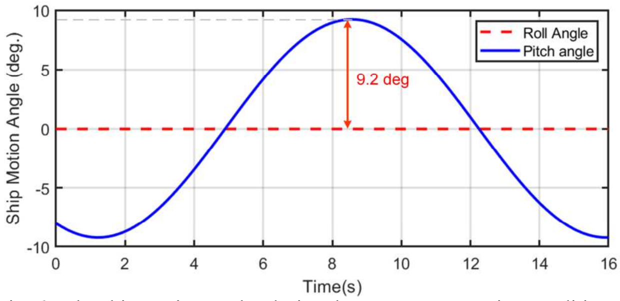

Fig. 6. The ship motion angles during the wave-encountering condition

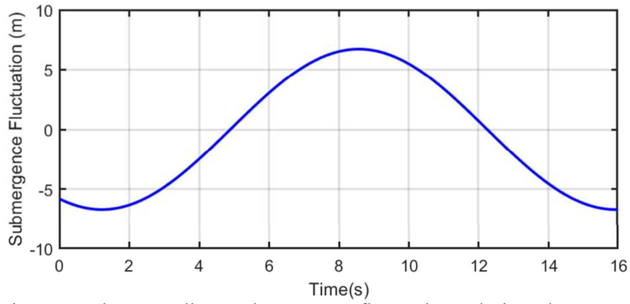

Fig. 7. The propellers submergence fluctuations during the wave-encountering condition

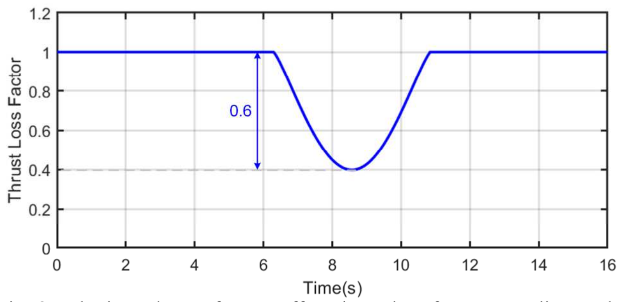

Fig. 8. The in-and-out-of water effect thrust loss factor according to the change of propeller immersion depth during wave-encountering

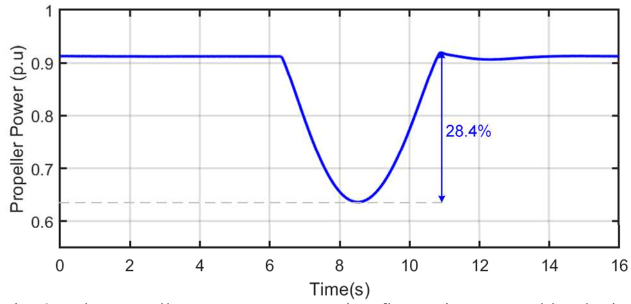

Fig. 9. The propellers power consumption fluctuations caused by the in-and-out-of-water effect during wave-encountering

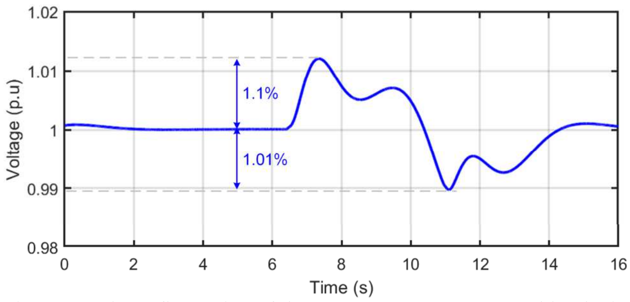

Fig. 10. Voltage fluctuation of the AES power system caused by the in-and-out-of-water effect during wave-encountering

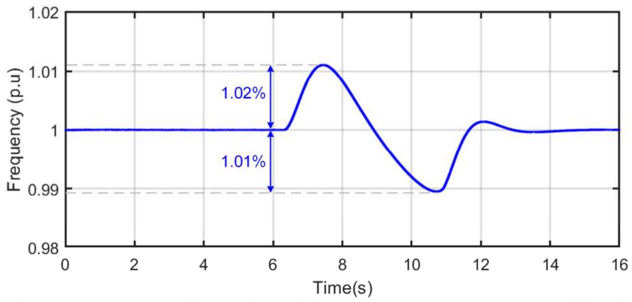

Fig. 11. Frequency fluctuation of the AES power system caused by the in-and-out-of-water effect during wave-encountering

depth fluctuations on the power system of all-electric ships is proposed. Different aspects of the proposed model framework and their interconnections are investigated. In addition, the basis of the proposed approach for analyzing the immersion depth of the propeller and the resulting thrust loss factor according to the wave characteristics have been presented. In the end, considering the typical ship and wave characteristics, a case study for a wave-encountering scenario has been explored. The simulations demonstrate that the effects of in-and-out-of-water on the AES power system voltage and frequency can be notable. For instance, it is shown that in the simulated sea environment, the frequency change amplitude of the AES power system is up to 1 percent. Therefore, these fluctuations should be investigated in different scenarios at the design and operating levels and the proposed integrated model can be helpful for model-based design, as well as control of the AES.

Based on the proposed model, a power management system for enhancing the power quality of the all-electric ships power system will be designed in future work.

ACKNOWLEDGMENT

This work was supported in part by the Reliable Power Electronic Based Power System (REPEPS) Project at the Department of Energy Technology, Aalborg University, as a part of the Villum Investigator Program, funded by the Villum Foundation, and in part by the Iran National Science Foundation (INSF) under Grant 98016308.

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